By Mike Bedford, G4AEE

Underground Radio

Communication for cave explorers

Crawling around in dark, muddy holes in the ground is not everyone's idea of entertainment. Yet for an estimated 100,000 people worldwide—mainly in the USA, UK and France—an environment of twisting subterranean passages, waterfalls, vast chambers, underground rivers, stalactites and stalagmites holds an inexplicable fascination. This is the world of the *caver* or *potholer* as we call them in the UK—or *spelunkers*, as they are called in the US.

If you must struggle to comprehend the appeal of the underworld, then the idea of radio experimentation underground will surely seem even more bizarre. Nevertheless, this is exactly the sort of activity that members of the UK's Cave Radio & Electronic Group (CREG) are involved in. This introduction to cave radio will look at the problems and techniques associated with through-rock communication.

Why Cave Radio?

Spelunking as a sport isn't without its cost. People don't always take adequate safety precautions; as a result, accidents happen. In particular, people get lost, fall down shafts, get cut off by rising water, get jammed tight or are washed away in floods. The UK is served by 14 cave rescue groups—all manned by volunteers—who are called out in the event of these emergencies.

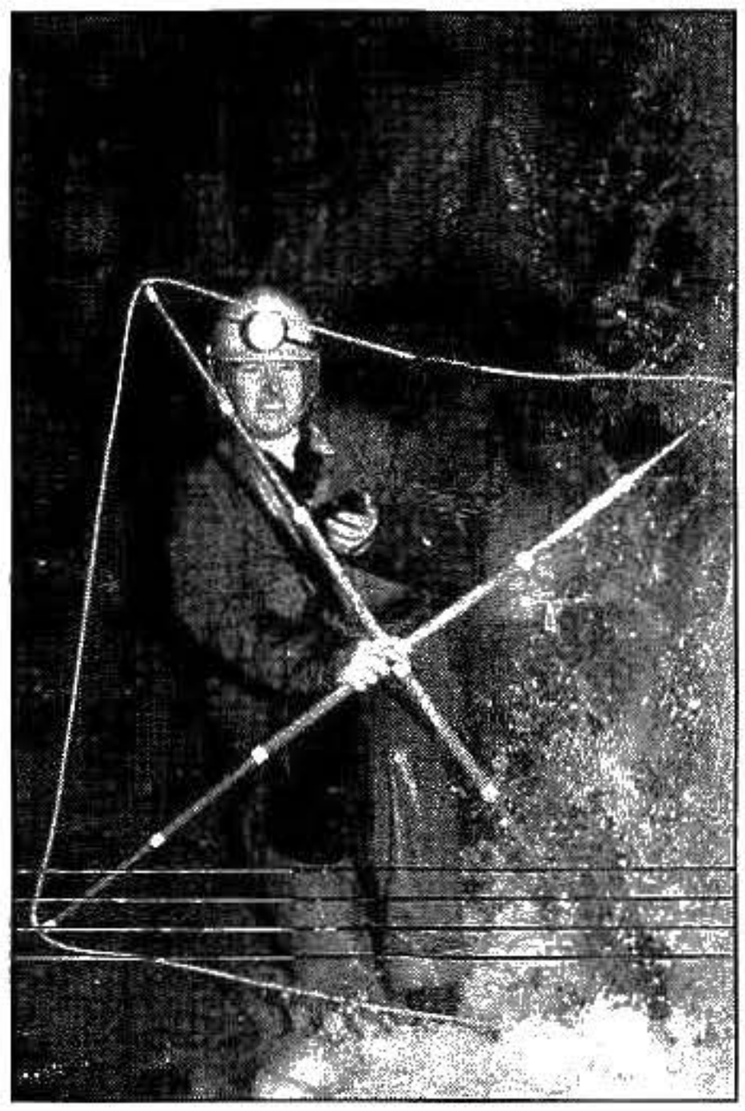
Most of these rescue groups make extensive use of special "cave radios," specifically the Molefone developed by Bob Mackin of Lancaster University and the Ogofone (ogof is Welsh for cave) designed by Bob Williams and Ian Todd of the South Wales Caving Club. If a casualty needs medical attention, radios can be used to call a doctor. If an underground rescue party finds that they need some special equipment, then this can be summoned from the surface—once again, time can be of the essence. And if a missing caver is found alive and well in the local pub (yes, it does happen) then the rescue party can be called back. In fact, rescue communication is the primary application of cave radio and is a major motivating factor for people developing new techniques.

What's Special About Cave Radio?

Forgive me for stating the obvious, but radio waves don't propagate too well through rock. I guess we're all aware of that, but what many people don't realize is that if the frequency is low enough, then acceptable ground penetration can be achieved. In fact, the optimum frequency depends on a number of factors, including the depth of the cave and the rock's conductivity. Caves form in limestone, which is not especially conductive. In dry rock, frequencies up to about 200 kHz can be used; in the wet limestone typical of most British caves, 30 to 100 kHz is more suitable.

At first sight, therefore, we have a viable means of communicating between a cave and the surface. However, a bit of further thought will reveal a potential problem. Many radio amateurs struggle to erect an efficient antenna for the 160-meter band because of space limitations. At 200 kHz, the wavelength is 10 times longer than at 160 meters, and at 30 kHz, a half-wave dipole would be about three miles long. Antennas for use in small cave passages would have to be very short indeed. A three-foot whip at 30 kHz or even 200 kHz would be grossly inefficient and very little power would be radiated.

As radio amateurs, we're used to the



Caves are a hostile environment for electronic equipment. Users probably wouldn't choose to set up a station under a waterfall, but the radio has to withstand this sort of treatment.

Cavers have achieved considerable success using CB rigs driving LF transverters. Ian Drummond, VE6IXD, is shown using his CB with LF transverter to talk with cavers in an abandoned iron mine in the Forest of Dean.

The CB and LF transverter is shown in action here in Kingsdale Master Cave in North Yorkshire. Although these radios have achieved good range, the CB rigs are not as rugged as other radios designed specifically for cavers.

concept of *radiation*, that is the flow of power through free space by electromagnetic radiation. However, radiation is only the dominant effect at more than a wavelength or so from the antenna and is therefore referred to as the *far field*. Much closer to the antenna, the *near field* dominates. This is subdivided into an electric field called the *electrostatic field* and a magnetic field called the *induction field*. The induction field differs from the radiated far field in a number of important respects.

The good news about the induction field is that it can be generated efficiently using an antenna much smaller than a half-wavelength. A multi-turn loop is, in fact, the classic means of generating an induction field. The bad news, however, is that unlike the radiated E and H fields, which both decay linearly with distance, the induction field drops off with the cube of distance, so it is inherently a very local phenomenon, as its name suggests. However, if we bear in mind that we're only aiming to communicate between the surface and a cave a few hundred yards below ground, this is not necessarily an insurmountable problem. Receiving the induction field is no problem either; a voltage is induced in another multi-turn loop and is then amplified, just like "real" radio. What I've just described is really a transformer with very wide separation between its primary and secondary windings—this is a very useful way of thinking about an inductive communication system.

Some Interesting Facts

Although I stated that the inverse cube law isn't a problem for cave communication, that is really an oversimplification. In fact, it is responsible for many of the challenges of cave radio. The strength of the induction field generated by a loop depends on its magnetic moment, which is controlled by three factors: the current flowing in the loop, the number of turns, and the area of the loop. If we now take this information together with the inverse cube law, we can draw some interesting, if somewhat depressing, conclusions.

Let's assume that we have a cave radio with a three-foot-diameter, 10-turn loop, and a current of 1 A flowing in the loop on transmit. This cave radio achieves a range of 600 feet, and the aim is to increase it to 1200 feet. Now, from the inverse cube law, it is clear that we have to increase the magnetic moment by a factor of 8.

One approach is to increase the current flowing in the loop by a factor of 8. If everything else about the loops remains constant, this could be achieved by putting the power amplifier voltage up by a factor of 8. However, this means that we end up consuming 64 times the power—hardly ideal for portable equipment running off batteries.

Naively, we may assume that a more reasonable approach would be to increase the number of turns on the loop to 80. However, if the thickness of the wire remains constant, the resistance of the loop will increase by a factor of 8, the current flowing in the loop will therefore decrease by a factor of 8, and so the magnetic moment will remain unchanged. Of course this increase in resistance could be alleviated by using thicker wire, but the antenna would then be 64 times heavier—not ideal for portable use in a cave. Alternatively, the current decrease could be canceled out by increasing the power amplifier voltage by a factor of 8. In this case, however, we are talking of an eightfold increase in the antenna weight and an eightfold increase in power. Once again, the requirements of portability means that this certainly isn't a good solution.

From an electrical viewpoint, the most promising way forward is to increase the area of the loop. To get the eightfold increase in magnetic moment, we need an eightfold increase in area, which equates to increasing the diameter by a factor of 2.828 (the square root of 8). As before, if everything else stays equal, we'll have to double either the thickness of the wire or the power amplifier voltage to cancel out the corresponding increase in resistance, but this is far better than the previous scenario. The fly in the ointment, however, is the ergonomics. A loop almost nine feet in diameter would be unusable in many cave passages, and the three-foot (actually, one-meter) loop has virtually become the *de facto* standard. Even so, for some cave passages, this is too large.

So, just as in conventional Amateur Radio, the sledgehammer approach of more power is not the way forward. In fact, because of the inverse cube law, it makes even less sense here. Unlike ordinary radio, however, the advice of putting all your effort into improving the antenna has its problems too. This highlights the importance of the receiver front end, an area in which many cave radio experimenters are expending their effort. For long range, cave radios need very sensitive, ultra-low-noise front ends.

A Radio that Will Take the Knocks

Caves are wet and muddy, and spelunkers often can't afford to pay too much attention to the kit they're carrying when they're hanging halfway down a 350-foot shaft. Electronic equipment is delicate and intolerant of water. Not only does equipment have to function correctly in the workshop, it has to continue to do so after being trodden in the mud, dropped in a pool of water, or knocked against a rock face. Furthermore, spelunkers and cave rescue team members are not necessarily trained radio operators, so any equipment must be simple to operate. In other words, ruggedization and ergonomics are very important in this field of radio. Think about these points as you look at the photographs accompanying this article.

A Link with Amateur Radio

Many of the world's cave radio experimenters are radio amateurs. Radio amateurs in a few countries now have allocations at LF, so there is scope here for true amateur cave radio. But even though most countries don't yet have an amateur LF allocation, there are still avenues for amateur work in cave radio. For example, at a recent field meeting, members of the CREG attempted 2-meter and 70-cm communication within caves, as opposed to through the rock. Although the aim of achieving long-distance communication by multiple reflections off the cave passages was not realized, VHF and UHF is, of course, eminently suitable for line of sight work.

One of the most well-publicized examples of a link-up between Amateur Radio and cave radio took place in April 1995. As a joint venture between cave radio enthusiasts and Amateur Radio clubs, special-event stations GB2CRO and GB4CRO were set up in caves in Northern England and South Wales, respectively. Both stations used low frequency induction radio to link the cave to the surface, with a repeater-type link from

the induction radio to a conventional HF station. This way, operators hundreds of meters underground were able to have amateur contacts around the world. The highlight of this weekend was a contact between the two underground stations 150 miles apart, achieving a world first—cave-to-cave communication via Amateur Radio. But this wasn't just for fun—interfacing induction radios to conventional radios, can be valuable to cave rescue organizations.

Licensing

Induction radio is not true radio and is inherently a very local form of communication. We might hope and expect, therefore, that the authorities would take a somewhat relaxed view of licensing. Unfortunately, this is not the case, and in most countries the use of induction radio is restricted in the same way as conventional radio. However, there are a few possible routes for legal experimentation. First of all, there are no international restrictions on the use of frequencies below 9 kHz, so it is up to the authorities in each country to decide whether to impose any restraint. In the UK, this band is regulated, but I understand that this is not the case in the USA. This band is not suitable for speech communication, but is valuable for Morse or data communication—and also for radiolocation, another important application of cave radio. Experimenters in the USA may also be able to make use of the 180-kHz band. In the UK, the primary method of experimenting with induction radio is through a commercial test and development license, although this is an expensive option for an amateur experimenter. I assume that a similar license is available in most countries.

The other possible avenue for cave radio experimentation is via amateur LF allocations. In the UK, an experimental allocation centered on 73 kHz was announced in May 1996. Although this isn't intended specifically for cave radio, it is, nevertheless, eminently suitable for this purpose. Negotiations for a Region 1 LF allocation at about 147 kHz are also under way. A few Australian amateurs currently have experimental LF permits, and there are hopes of a more general allocation at 160 to 190 kHz. Amateurs in New Zealand and Papua New Guinea already have a low frequency band.

The CREG

This article has provided a very brief introduction to cave radio. If you want to know more, there is a wealth of information published by the Cave Radio & Electronics Group. The CREG is a special interest group of the UK's British Cave Research Association, with about 170 members in 20 countries, is currently the world's most active group in cave radio research. A year's subscription, including four copies of our journal, costs £10 (surface) or £12.40 (air mail) in the USA. Funds must be paid by credit card, banker's draft in pounds sterling or UK banknotes.

For further information, either e-mail David Gibson at **gibson@mcrosolv.demon.co.uk**, or (in the USA) send a stamped, self-addressed envelope to Steven Shope at Sandia Research Associates Inc, 3411 Candelaria NE, Albuquerque, NM 87107. Please note that Steven has agreed only to distribute information sheets, so please don't write requesting an individual reply. Outside the USA, please write to the author, enclosing an International Reply Coupon or (in the UK) a stamped, self-addressed envelope.

The World Wide Web site of the Cave Radio and Electronics Group can be found at **http://www.Sat.dundee.ac.uk/~arb/creg/**.

If a transmitting loop is set up underground to be level and rigid, the position on the surface directly above it can be determined with accuracy. Then an above-ground measurement from a second location can be made of the angle of arrival of the underground signal. Using the separation of the two above-ground locations and the angle of arrival, trigonometry can be used to determine the depth below the surface of the underground radio.

Safety Warning!

One of my main reasons for writing this article was to encourage radio amateurs to experiment with cave radio. As more people work in this fascinating area, new developments will eventually be made available to the cave rescue groups worldwide. It is not overstating the case to say that lives may be saved as a result.

But it would be wholly inappropriate if, as a result of this article, inexperienced people were enticed underground—unsupervised. Caves are dangerous places, but most of the risks can be eliminated if you know what you're doing. So, if this article has ignited a spark of interest, by all means start experimenting with cave radio. But when the time comes to test it underground, make contact with your local speleological club (in the USA the local clubs are called "grottos" and are affiliated with the National Speleological Society), who can guide you underground safely.

Mike Bedford, 4 Holme House, Oakworth, Keighley, West Yorkshire BD22 0QY, UK, has been licensed as G4AEE since 1971. He has been caving for about 15 years, and merged his two interests 10 years ago. He is currently the Chairman of the CREG, and editor of the group's technical journal. Mike has worked for a number of years in the electronics and computer industries, and has written extensively for electronics and computing magazines. Mike works as a technical marketing consultant in the world of electronics and computing. Photos were made by the author.

The Ogophone in action in Ogof Ffynnon Ddu cave is South Wales. Note the rugged, simple telephone handset and the army surplus ammo boxes used to carry it.